Ship Automatic Collision Avoidance by Altering Course Based on Ship Dynamic domain

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***Abstract*—The purpose of this paper is to improve the automatic collision avoidance procedure of two ships stipulated in open sea areas without the disturbances of wind, wave and current, which is achieved by altering course based on ship dynamic domain. As the rapid increase in the study of ship collision risk index (CRI) and automatic collision avoidance decision-making for ships, the decision-making process is fully recognized. In this paper, the model of ship dynamic domain are adopted and a series of simulation studies are made. The safe distance of approach (SDA) is determined by ship dynamic domain. Then ship automatic collision avoidance procedure is established to controlling course alteration for collision avoidance. Experimental results show that ship dynamic domain is suitable to collision avoidance. The key factor that leads to the in validation is the CRI and course alteration. Based on the seagoing experience and simulation, the decision-making for collision avoidance in three encounter situations is accurate enough for this application. The results provide a reference that compute and display the ship parameters fast and accurately to decision-making process of ship collision avoidance.**

Keywords—ship dynamic domain; collision risk index; encounter situation; course alteration

I. INTRODUCTION

The decision-making of ship collision avoidance depends on a series of ship operations, the whole decision-making process can be summed by "discovery, judgment, avoidance". The survey of maritime accidents notes that 80% of maritime accidents are related to human factors, so it is necessary to focus on the decision-making process of ship collision avoidance.

The definition of ship domain was firstly proposed by FuJii Y [1] in the study of waterway traffic capacity. In the seventies of last century, Goodwin's studies had shown the existence of ship domain and obtained the model of ship domain in open sea area [2]. Sun Licheng [3] built the model of ship domain in open sea area by investigating the ship collision avoiding measures of questionnaire. Thereafter, Zbigniew [4] built the ship fuzzy domain. Then the model of ship domain based on AIS datas was established.

People started to the research of decision-making process of ship collision avoidance from the qualitative study of the International Regulations for Preventing Collisions at sea (COLREGS) to quantitative study of ship collision risk in fifties of last century. Determining the existence of ship collision risk according to the target ship's bearing and changes of distance [5]. Determining the time and measure of avoiding collision according to distance of approaching. Determining the existence of collision risk between own ship and target ship, the times and measures of avoiding collision according to the distance of closest point of approaching (DCPA) and time to closest point of approaching (TCPA).

The course and speed alteration of avoiding collision is the most prominent in the research of ship collision avoidance.On the basis, Bi Xiuying, Jia Chuanying [6] established the distance of the last minute action and model of avoiding collision. In order to study the influences of ship's maneuverability on DCPA, Yang Yansheng [7] proposed the concept of ship dynamic collision avoidance system, which is established on the basis of geometry for collision avoidance with control theory from the point of ship maneuverability.

This paper is organized by several sections. Section 2 presents the calculation of ship motion parameters .Section 3 presents the model of dividing encounter situations. Section 4 presents the decision-making process of ship collision avoidance. Section 5 presents the simulation study in three encounter situations. Section 6 concludes this paper.

II. SHIP MOTION PARAMETERS

A. The Calculation of DCPA and TCPA

In this study, we adopt the Nomoto model to simulate the ship. The ship course controller uses a PID controller. The

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system is always in automatic control mode in normal navigation and achieves a closed-loop control. The manual and automatic control modes can be switched freely [8].

Suppose the velocity of own ship s_s is v_s, the heading of the ship is φ_s, and the location is $\left(\mathrm{X}_s, \mathrm{Y}_s\right)$. the velocity of target ship s_t is v_t, the heading of the ship is φ_s, and the location is $\left(\mathrm{X}_t, \mathrm{Y}_t\right)$. Consequently, in the ship motion simulation system, the ship motion parameters can be calculated as shown in *Fig. 1*.

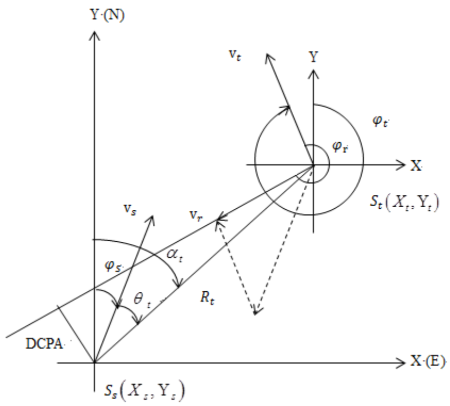

Fig. 1. Relative motion parameters chart.

The true motion velocity of the own ship is given by:

$$\begin{cases} v_{\mathrm{xs}} = v_s \cdot \sin(\varphi_s) \\ v_{\mathrm{ys}} = v_s \cdot \cos(\varphi_s) \end{cases} \tag{1}$$

The true motion velocity vector of target is given by:

$$\begin{cases} v_{xt} = v_t \cdot \sin(\varphi_t) \\ v_{yt} = v_t \cdot \cos(\varphi_t) \end{cases} \tag{2}$$

The relative motion velocity of the target ship is given by:

Relative motion velocity component

$$\begin{cases} v_{xr} = v_{xt} - v_{xs} \\ v_{yr} = v_{yt} - v_{ys} \end{cases} \tag{3}$$

Relative motion velocity

$$v_r = \sqrt{v_{xr}^2 + v_{yr}^2} \tag{4}$$

Relative yaw angle

$$\varphi_r = \begin{cases} \dfrac{\pi}{2} & v_{yr} = 0, v_{xr} \geq 0 \\ \dfrac{3\pi}{2} & v_{yr} = 0, v_{xr} < 0 \\ \arctan\left(\dfrac{v_{xr}}{v_{yr}}\right) + \alpha_1 & v_{yr} \neq 0 \end{cases} \tag{5}$$

Where $$\alpha_1 = \begin{cases} 0 & v_{xr} \geq 0, v_{yr} \geq 0 \\ \pi & v_{yr} < 0 \\ 2\pi & v_{xr} < 0, v_{yr} < 0 \end{cases} \tag{6}$$

The true bearing of the target ship relative to the own ship is given by:

$$\alpha_t = \begin{cases} \dfrac{\pi}{2} & Y_t - Y_s = 0, X_t - X_s \geq 0 \\ \dfrac{3\pi}{2} & Y_t - Y_s = 0, X_t - X_s < 0 \\ \arctan\left(\dfrac{X_t - X_s}{Y_t - Y_s}\right) + \alpha_2 & Y_t - Y_s \neq 0 \end{cases} \tag{7}$$

Where $$\alpha_1 = \begin{cases} 0 & v_{xr} \geq 0, v_{yr} \geq 0 \\ \pi & v_{yr} < 0 \\ 2\pi & v_{xr} < 0, v_{yr} < 0 \end{cases} \tag{8}$$

The relative bearing of the target ship is given by:

$$\theta_t = \alpha_t - \varphi_s \pm 360^{\circ} \tag{9}$$

The crossing angle of the own ship and the target ship is given by:

$$C_t = \varphi_t - \varphi_s \tag{10}$$

The relative distance of the target ship is given by:

$$R_t = \sqrt{\left(X_{\mathrm{t}} - X_s\right)^2 + \left(Y_{\mathrm{t}} - Y_s\right)^2} \tag{11}$$

DCPA is computed as:

$$DCPA = R_t \cdot \sin(\varphi_r - a_t - \pi) \tag{12}$$

The DCPA of the target ship has a relationship of the bow bearing of the own ship. If the target ship is located in the starboard of the ship $C_t \in \left(0^{\circ} \sim 180^{\circ}\right)$ and the target ship will pass the bow of the own ship, DCPA is a positive value; otherwise, it is a negative value. If the target ship is located in the starboard of the ship $C_t \in \left(180^{\circ} \sim 360^{\circ}\right)$ and the target ship will pass the bow of the own ship, DCPA is a negative value; otherwise, it is positive.

TCPA is computed as:

$$TCPA = R_t \cdot \cos(\varphi_r - \alpha_t - \pi) / v_r \tag{13}$$

When the TCPA is positive, there is still a collision risk existing between the own ship and target ship; When the TCPA is negative, the own ship passed away the target ship, there is no collision risk existing between the own ship and target ship.

B. The Calculation of SDA Based on Ship Dynamic Domain

COLREGS, 1972, Rule 8, "Action taken to avoid collision with another vessel shall be such as to result in passing at a safe distance" is commonly used formula to represent the two ships could pass safely.

$$DCPA \geq SDA \tag{14}$$

Goodwin's ship domain model is applicable to various encounter situations in open sea areas, so using Goodwin's model is reasonable in here. The calculation of SDA is based on ship dynamic domain, which will be some domain fuzzy boundaries [9], so this situation should be divided into the domain of the ship safe distance of approach. In this paper, the values of domain in four bearings are amended to make the domain change continuously in Table 1.

TABLE 1. The Domain Value Around Ship

Relative Bearing of The Target Ship	000	090	180	270
Domain Value(n mile)	0.85	1.18	1.02	0.85

$$domain=\begin{cases} 0.85-\dfrac{\theta_t}{180^\circ}\times 0.2 & 0^\circ \leq \theta_t \leq 112.5^\circ \\ 1.18-\dfrac{\theta_t}{180^\circ}\times 0.73 & 112.5^\circ \leq \theta_t \leq 180^\circ \\ 1.02-\dfrac{360^\circ-\theta_t}{180^\circ}\times 0.57 & 180^\circ \leq \theta_t \leq 247.5^\circ \\ 0.85-\dfrac{360^\circ-\theta_t}{180^\circ}\times 0.3 & 247.5^\circ \leq \theta_t \leq 360^\circ \end{cases} \tag{15}$$

d_1 is given by making the domain smoothly and changing continuously. d_2 is another value of SDA, generally speaking, when the initial encounter from the ship, DCPA greater than d_2, it can be regarded as completely without considering collision avoidance measures, the correction value of d_1, d_2 is given by:

$$d_1 = domain \times (1+0.276) \tag{16}$$

$$d_2 = 2 \times domain \tag{17}$$

Fig. 2 present the ship domain of own ship plotted by MATLAB in this paper.

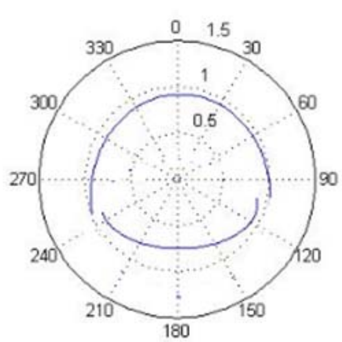

Fig. 2. The domain of own ship

III. THE MODEL OF DIVIDING ENCOUNTER SITUATION

In the navigation, the encounter status of ships is divided into head-on, crossing, and overtaking situations when two ships encounter in good visibility. *Fig. 3* indicates the encounter situations. In the ship collision avoidance decision-making supporting system, we must judge the encounter situation according to the information of the ship in order to determine the collision avoidance strategy in accordance with the COLREGS. Therefore, the motion simulation system of the ship is used to prove the validity of the ship collision avoidance under different encounter situations [10].

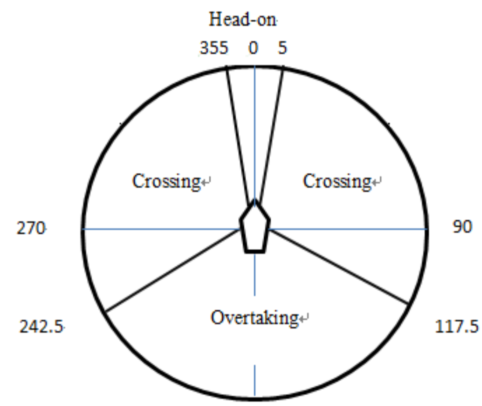

Fig. 3. The Encounter situation

(a) Overtaking situation is determined by

(1) $107.5^\circ+\varphi_t \leq \varphi_s+\theta_t+180^\circ \leq 252.5^\circ+\varphi_t$ (for avoiding in harmonious collision)

(2) $TCPA>0$

(3) $v_s > v_t$ and

(4) $R_t \leq 3$ n mile

(b) Head-on situation is determined by

(1) $\theta_t \leq 5^\circ$ or $\theta_t \geq 351^\circ$

(2) $174^\circ \leq |C_t| \leq 186^\circ$ and

(3) $u_T > 0$

(c) Crossing situation is determined by

(1) $0^\circ < \theta_t < 117.5^\circ$ or $242.5^\circ \leq \theta_t < 360^\circ$

(2) $0^\circ \leq |C_t| \leq 180^\circ$ and

(3) $u_T > 0$

Fig. 4 presents the flowchart of ship automatic collision avoidance strategy optimization is implemented according to the data sample of own ship and target ship. Then the ship parameter is calculated to judge the danger between two ships and the encounter situation. The optimization module can be realized between the modules "Danger ?" and "CRI > 0.5". The safe and economic decision-making for ship collision avoidance comes from numerous collision avoidance strategies, which fully conform to the COLREGS. It is important to accurately obtain and handle information, which can be obtained from AIS and GPS equipment.

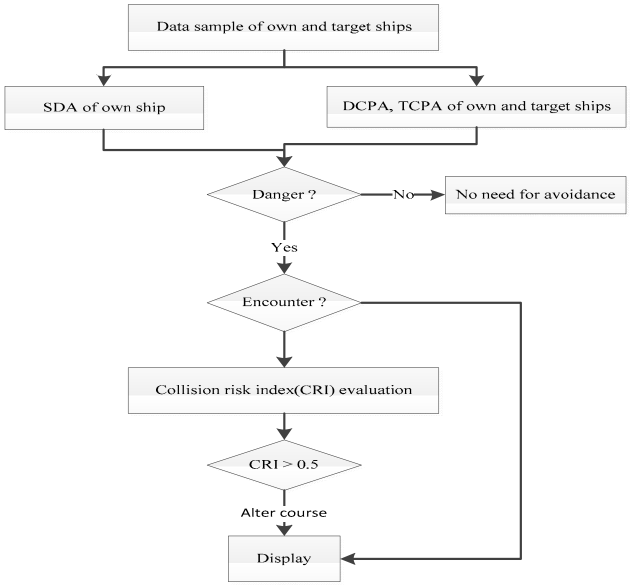

Fig. 4. The decision-making progress of ship collision avoidance

IV. THE FUZZY DECISION-MAKING PROCESS OF SHIP COLLISION AVOIDANCE

A. The Fuzzy Model of Collision Risk

The collision risk index of ship is random and fuzzy. It is a suitable method to calculate the collision risk index by DCPA and TCPA. Ship collision risk can be divided into Space collision risk (SCR) and time collision risk (TCR) in terms of space and time [11].

B. The Calculation of Collision Avoidance Risk

1) The Definition and Model of SCR

SCR is defined to determine the measurement of own ship collision risk by using target ship's SDA, bearing of SDA and relative bearing of the target ship as the main index.

Suppose the domain of DCPA is U_d , the fuzzy set of space collision risk is U_{dT} , then the membership function u_{dT} of U_{dT} is given by :

$$u_{dT}=\begin{cases}1 & |DCPA|<d_1\\ \left(\dfrac{d_2-|DCPA|}{d_2-d_1}\right)^{3.03} & d_1\le|DCPA|<d_2\\ 0 & |DCPA|\ge d_2\end{cases} \tag{18}$$

2) The Definition and Model of TCR

TCR is defined as the degree of time urgency when the own ship navigate to the point of Distance of Last Minute Action (DLA) [12].

$$DLA=12\text{L} \tag{19}$$

Suppose the domain of TCPA is U_t , the fuzzy set of space collision risk is U_{tT} , then the membership function u_{tT} of U_{tT} is given by :

$$u_{tT}=\begin{cases}1 & |TCPA|<t_1\\ \left(\dfrac{t_2-|TCPA|}{t_2-t_1}\right)^{3.03} & t_1\le|TCPA|<t_2\\ 0 & |TCPA|\ge t_2\end{cases} \tag{20}$$

From the point of safety, collision risk is supposed to exist in this paper. when the distance of two ships is 8 n mile. According to the statistical research and from a security point of view, DLA is generally about 12 times of ship length.

$$t_1=\frac{\sqrt{DLA^2-DCPA^2}}{v_r}\ ,\ t_2=\frac{\sqrt{8^2-DCPA^2}}{v_r} \tag{21}$$

3) The Prediction of Collision Risk

The collision risk is the combination of SCR and TCR, so the set of collision risk is defined as:

$$u_T=u_{dT}\cdot u_{tT}$$

According to the practice for ship collision avoidance at sea, following conclusions can be drawn:

(a) When SCR and TCR are not zero at the same time, there is existing a ship collision risk.

(b) The collision risk should be a gradual process, and mutations should not appear. Obviously the original model conforms to the first, but do not meet the second, so here we change the "Max" to the "min".

(1) $u_T=0$, if $u_{dT}=0$;

(2) $u_T=0$, if $u_{dT}\ne 0, u_{tT}=0$;

(3) $u_T=\min\{u_{dT},u_{tT}\}$, if $u_{dT}\ne 0, u_{tT}\ne 0$.

So we can conclude that the ship collision risk is changing from small to large continuously .It conforms to the actuality at sea.

C. The Degree of Course Alteration

After the C degree of course alteration, The true motion velocity of the own ship is given by:

$$\begin{cases}v'_{xs}=v_s\cdot\sin(\varphi_s+C)\\ v'_{Ys}=v_s\cdot\cos(\varphi_s+C)\end{cases} \tag{21}$$

Considering the course alteration is a progress, C is determined by increasing step at 0.1 degree, while $DCPA'>SDA$, there is a delay [13] as follow:

$$R'_t=R_t-0.5 \tag{22}$$

$$DCPA' = (R_t - 0.5) \cdot \sin(\varphi' - \alpha_t - \pi) \quad (23)$$

V. SIMULATION STUDY

In the simulation studies, we simulate three encounter situations to identify the decision-making for ship collision avoidance. In the most complex crossing encounter situation, different collision avoidance criteria are adopted to estimate the danger signal including the collision risk and ship domain. Different collision risk criteria are used to evaluate the collision avoidance process in the simulation.

A. Overtaking situation

In the simulation, there is no wind and waves, the initial parameters of own ship and target ship are as follows:

Own ship: $\varphi_s = 0^\circ$, v_s =16kn, coordination (5, 1) n mile.

Target ship: $\varphi_s = 0^\circ$, v_s =9kn, coordination (5, 7) n mile.

The analysis of encounter situation is concluded that the relative bearing of the target ship is 0°, the distance between the two ships is 3.5 n mile, and the encounter situation is overtaking situation. The parameters are calculated in Tab 2.

TABLE 2. The Results of Relevant Parameters in Overtaking Situation

v_r	7kn	TCPA	30min
φ_r	180°	u_{dT}	1
θ_t	0°	u_{tT}	0.6671
d_1	1.0846nm	u_T	0.6671
d_2	1.7000nm	t_1	8.94min
DCPA	0	t_2	68.5min

In the decision-making process, the own ship is give-way Vessel and the target ship is the stand-on vessel, the own ship turn left to avoid collision by 20.5 degrees. The simulation diagram for overtaking encounter situation is given in *Fig. 5* to identify the optimal collision avoidance measure.

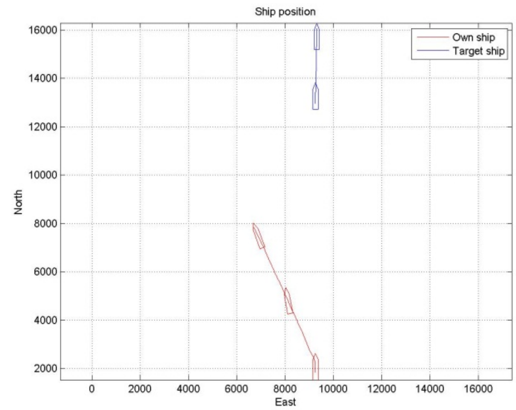

Fig. 5. The result of overtaking simulation

B. Crossing situation

In the simulation, there is no wind and waves, the initial parameters of own ship and target ship are as follows:

Own ship: $\varphi_s = 0^\circ$, v_s =12kn, coordination (4, 2) n mile.

Target ship: $\varphi_s = 270^\circ$, v_s =9kn, coordination (5.5, 6) n mile.

The analysis of encounter situation is concluded that the relative bearing of the target ship is 38.5433°, the distance between the two ships is 4.3 n mile, and the encounter situation is Crossing situation. The parameters are calculated in Tab 3.

TABLE 3. The Results of Relevant Parameters in Crossing Situation

v_r	17kn	TCPA	15min
φ_r	-135°	u_{dT}	1
θ_t	38.5433°	u_{tT}	0.5952
d_1	0.9861nm	u_T	0.5952
d_2	1.5457nm	t_1	4.0min
DCPA	0.6051nm	t_2	42.3min

In the decision-making process, the own ship is give-way Vessel and the target ship is the stand-on vessel, the own ship turn right to avoid collision by 30.4 degrees. The simulation diagram for crossing encounter situation is given in *Fig. 6* to identify the optimal collision avoidance measure.

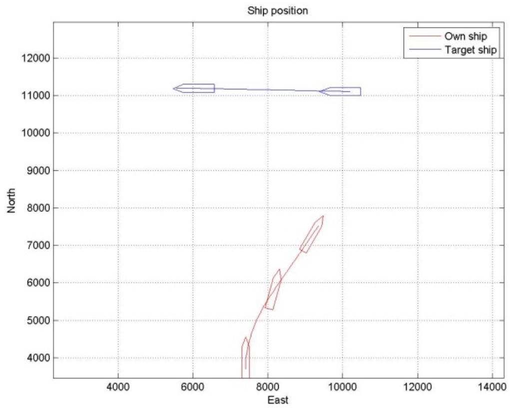

Fig. 6. The result of crossing simulation

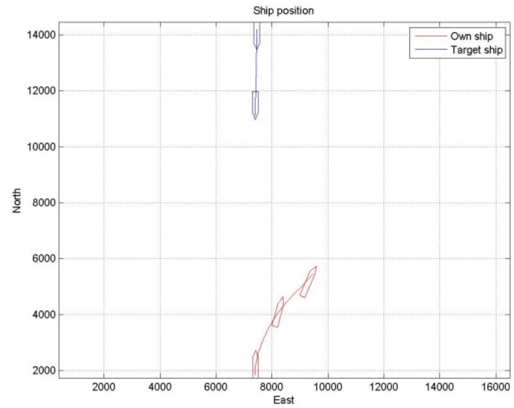

Fig. 7. The result of head-on simulation

C. Head-on situation

In the simulation, there is no wind and waves, the initial parameters of own ship and target ship are as follows:

Own ship: $\varphi_s = 0^\circ$, v_s =12kn, coordination (4, 1) n mile.

Target ship: $\varphi_s = 180^\circ$, v_s =12kn, coordination (4, 6) n mile.

The analysis of encounter situation is concluded that the relative bearing of the target ship is 0°, the distance between the two ships is 3.6 n mile, and the encounter situation is head-on situation. The parameters are calculated in Tab 4.

TABLE 4. The Results of Relevant Parameters in Head-on Situation

v_r	24kn	TCPA	30min
φ_r	180°	u_{dT}	1
θ_t	0°	u_{tT}	0.6952
d_1	1.0048nm	u_T	0.6952
d_2	1.5749nm	t_1	4.50min
DCPA	0	t_2	30.0min

In the decision-making process, the own ship is give-way Vessel and the target ship is the stand-on vessel, the own ship turn right to avoid collision by 30.6 degrees. The simulation diagram for overtaking head-on situation is given to in *Fig. 7* identify the optimal collision avoidance measure.

CONCLUSIONS

The decision-making progress of two ships collision avoidance is studied in open sea areas without the disturbance of wind, wave and current. A basic collision avoidance based on DCPA and TCPA is designed by applying the decision-making for ship collision avoidance. Whether there is a collision existing to identify the encounter situation, so the given-way ship (own ship) can make decision to avoid the collision by altering course. The research of ship motion parameters calculation and ship automatic collision avoidance by using the model of MMG and ship dynamic domain in three encounter situations. The reasonable and useful decision-making system of ship automatic collision avoidance was established by the model of MMG and ship dynamic domain. The encounter situations were simulated to evaluate the performance of the proposed formulation. The formulation can also be treated as a foundation and part of automatic collision avoidance system. The situation that all the involved ships comply with requirements from COLREs is considered.

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